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DIRECT AND INDIRECT VISIBLE RADIATION YIELD FROM A POINT SOURCE UNDER DIFFERENT WEATHER CONDITIONS

by

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Abstract

Measurements of ratios of scattered to direct thermal radiation in the visible region were made on 17 nights during the period from October 1960 to February 1961, at Oakhurst, New Jersey, between two and three miles west of the ocean shoreline. Source-to-receiver distances of approximately one and two miles were involved, with general weather conditions varying from close to two miles visibility, snow-covered ground, and overcast skies, to clear skies, no snow, and visibility greather than 20 miles.

Results indicate situations where the indirect or scattered radiation is appreciably greater than the direct radiation. Tentative empirical relationships are derived for a 180° receiver field of view in a hazy atmosphere for some of the cases where no snow and cloudless skies exist, and compared with those of several previous investigators in the field. Results are also presented for cases involving snow-covered ground and or clouds. An empirical relationship is tentatively developed for the situation involving only the presence of snow. In addition, some consideration is given to the multiple-scattering problem.

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DIRECT AND INDIRECT VISIBLE RADIATION YIELD
FROM A POINT SOURCE UNDER DIFFERENT WEATHER CONDITIONS

INTRODUCTION

Transmission of visible light radiation through the earth's atmosphere is dependent on the concentration and distribution of gaseous constituents and suspended particles in the atmosphere called aerosols. These aerosols are dependent on meteorological conditions, particularly in the lowest 30,000 feet or so of the atmosphere; i.e., the troposphere region where continuous and extensive changes occur in the aerosol content. It is such changes that cause wide and predominant variations in the scattering effects involved in direct as well as indirect visible radiation transmission.

A 1957 AEC publication, entitled "The Effects of Nuclear Weapons," obtainable through the Government Printing Office, shows the extent of thermal damage that can occur for different substances at various distances from a nuclear blast. A correlation factor is also included to indicate the effects of the weather in terms of the total transmissivity of the atmosphere. This factor, however, was determined for very limited weather conditions; namely, good visibility, cloudless skies, and negligible ground albedo effect. Unclassified reports issued since 1957 by those engaged in related investigations also indicate a limited view with respect to the ground albedo and/or cloud albedo factors.

This report, therefore, attempts to determine the significance of the added ground albedo and/or cloud-coverage effects and to substantiate some previous results of other investigations made in the absence of any significant albedo factor. Furthermore, the effects of multiple scattering, almost totally ignored for such measurements in the past, are considered here to some extent.

The problem of determining direct versus indirect visible radiation from a point source under different weather conditions has become increasingly significant in the past 15 years. In addition to its effect on certain theoretical aspects of radiation transfer in the atmosphere, it now has a high degree of practical significance involving thermal radiation damage from nuclear detonations.

BACKGROUND

The Naval Research Laboratory, Washington, D. C., and the Naval Radiological Defense Laboratory, San Francisco, California, have accomplished much in the past decade to show the relationship between direct and scattered light under various weather conditions and receiver distances and fields of view at or near ground level. Duncan[1] of NRL in 1956-57 extended the prior work of Stewart and Curcio[2] of NRL to include a field of view of 50° and also considered data for transmittances less than 0.1. His results show that Stewart and Curcio's semiempirical relationship for relatively clear atmospheres, $T_\theta = T + k(1 - T)(1 - e^{-\theta})$, holds for $k = 0.5$ when $T \geq 0.1$; and when $T \leq 0.1$, $k = 0.5 - 3.5\,(0.1 - T)$, where T_θ = total transmission, T = collimated transmittance, θ = receiver field of view in radians, and k = ground albedo and space leakage factor. Stewart and Curcio considered only single-type scattering, both empirically and theoretically, without regard to source-receiver distance effects. Duncan took account of the multiple-scattering effect empirically, without regard to source-receiver distance effects.

In 1957, Gibbons[3] of NRDL extended the 1.5 nautical mile range of Duncan to 14 miles and extended receiver fields of view up to 117°. Theoretical calculations made by Gibbons[4] for a hazy type of atmosphere and for a 180° receiver field of view show a close correlation for the ratio of scattered to direct light radiation, i.e., H, with those of Stewart and Curcio at an optical path near 0.3 and below; while at values of 0.9, 1.2, and 3.6, his results are lower by factors of about 1.5, 2, and 12, respectively, as shown in Fig. 1. A comparison of Duncan's semiempirical

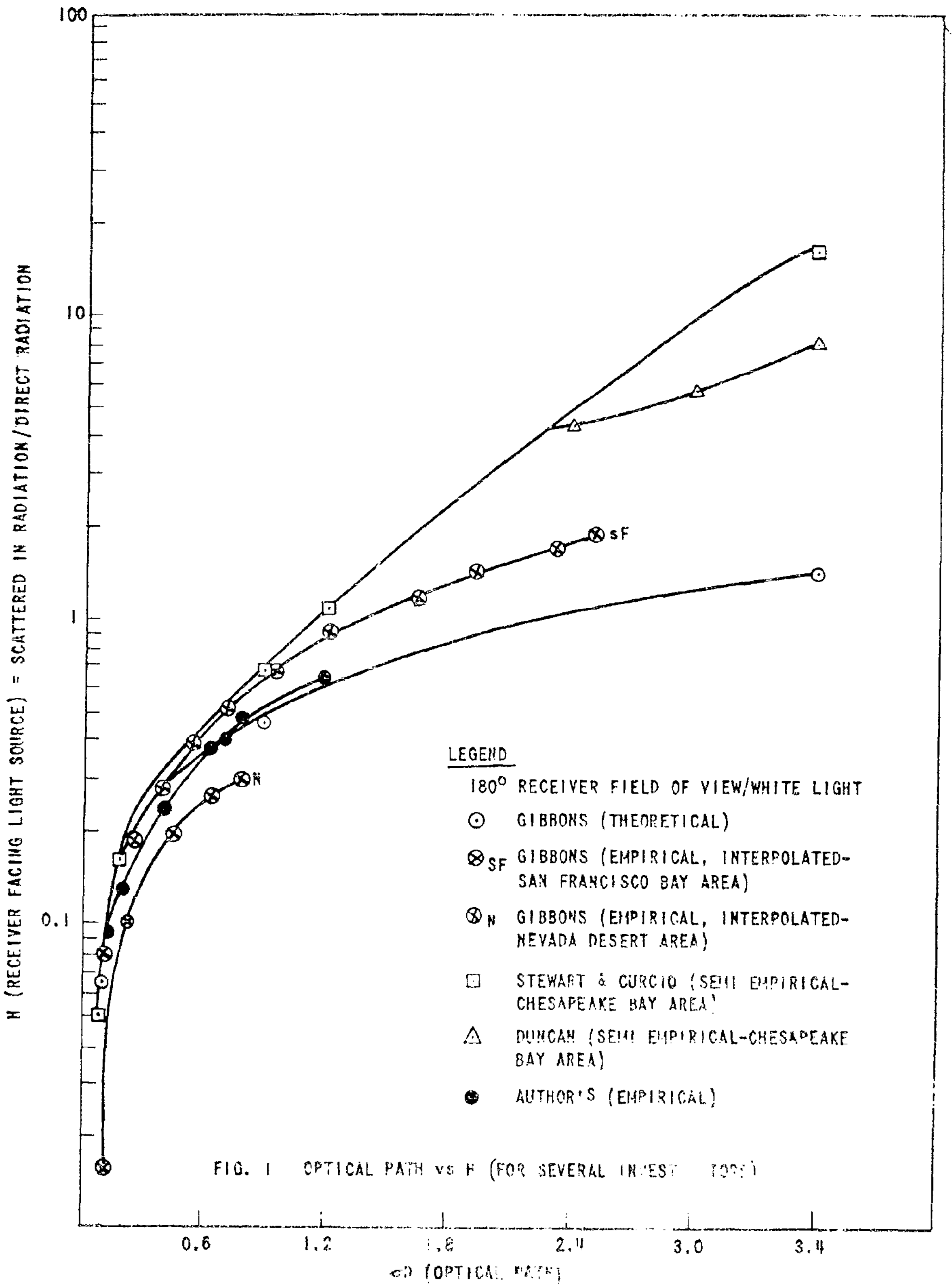

FIG. 1 OPTICAL PATH vs H (FOR SEVERAL INVESTIGATORS)

formula with that of Gibbons indicates a somewhat closer relationship than that of Stewart and Curcio for cases where the optical path exceeds 2.3. Gibbons' general relationship[4] shows

$$H = \frac{\text{scattered in radiation}}{\text{direct radiation}} = \frac{T_\theta - T}{T}$$

$$= 2\pi g k \sigma D e^{\sigma D} \int_{0^+}^{R_2} \int_{0^+}^{\psi} \frac{B(\phi) e^{-(R_1 + R_2)\sigma D} \sin \psi \cos \psi \, dR_2 d\psi}{R_1^2} \qquad \text{(See Fig. 2)}$$

where g = the surface albedo effect, k is a proportionality constant for a specific type of atmosphere, $B(\phi)$ is the phase function which, when multiplied by $k\sigma$, yields the unit volume scattering function for a specific scattering medium; σD is the optical path; $R_1 = \frac{r_1}{D}$ and $R_2 = \frac{r_2}{D}$, where r_1 = distance of the source to the scattering volume element; r_2 = distance of the scattering volume element to the receiver; D = the distance between the source and receiver; ψ = angle of incidence of the scattered light on the sensitive receiver; and ψ = receiver field of view divided by 2. The aforementioned geometric factors are indicated in Fig. 2.

As in the case of Stewart and Curcio and also Duncan, the atmosphere is considered as infinitely homogeneous, and cloud reflections are not taken into account. Gibbons' derivation also allows for scattering of radiation away from the receiver after once it has been scattered toward the receiver, i.e., in the case of multiple scattering; it does not consider the scattering in of radiation once it has been scattered out, i.e., in the case of single scattering. Gibbons[5] also measures the "H" factor for one case of full cloud cover and visibility exceeding 50 miles, with the source to the receiver distances varying from about 1 to 17 miles.

DISCUSSION

General

The equipment employed in obtaining the data in this report consisted essentially of the flashlight arrangement described in USASRDL Technical Report 2152.[6] The principal modification consisted in replacing the ground glass over the photomultiplier aperture with a one-inch-diameter opal glass, and sandblasting the side facing the incident light. This change brought about an improved cosine response of the larger angles of incidence and improved the left-to-right symmetrical response so that a maximum correction factor was involved that did not exceed 10%, without a filter, and was about 15% with a filter. A General Electric FT 503 flash tube was used for three tests instead of the Sylvania 4330. The receiver holder was modified so that vertical measurements as well as horizontal plane measurements could be readily made. Experimental checks in the laboratory indicated that the edge effects had a negligible overall effect for all the fields of view, except at 45°. In this case, a 10% cutoff occurred at a 50° field of view and a 90% cutoff at a 60° field of view.

Experimental Procedures

At first occulters of 2-1/2-inch diameter and later those of 3-1/2-inch diameter were employed at the near site, about 6200 feet from the source, and at the far site, approximately 10,000 feet from the source, so that less than a 1/2° field of view was subtended from the occulter to the receiver-detector element. The amount of scattered light was measured with the above-mentioned occulter blocking out the direct light. The total or direct light, plus the indirect light, was measured when the occulter unit was lowered. The difference in the two measurements then yielded the direct component.

$$H = 2\pi g k \sigma D \; e^{\sigma D} \int_{0^+}^{R_2} \int_{0^+}^{\Psi} \frac{B(\phi)\, e^{-(R_1+R_2)\sigma D} \sin\psi \cos\psi \, dR_2 \, d\psi}{R_1^2}$$

where $R_1 = \dfrac{r_1}{D}$

$R_2 = \dfrac{r_2}{D}$

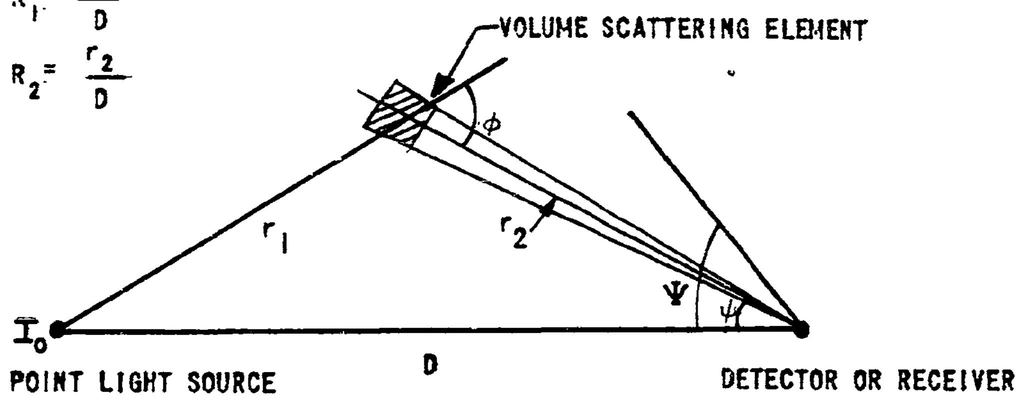

FIG. 2 CONFIGURATION FOR DETERMINING THE H INTEGRAL (GIBBONS)

The sequence of measurements varied twofold, depending on the prevalence of stable or unstable weather conditions. In stable weather, measurements were generally taken during a complete run so that the total light was sequentially detected for the no-filter and color-filter cases for the 180°, 135°, 90°, and 45° fields of view. The scattered light was then sequentially detected in the same order. During an unstable weather situation, the scattered light was measured immediately after the total-light measurements for a given field of view for the no-filter and the color-filter. The same pattern was then followed for the other fields of view.

Ten discrete readings were taken for each total-light value and then averaged, whereas five readings were taken for each scattered-light value and averaged. Ten readings for each total-light value permitted a better average because of the rapid fluctuations or scintillations of the direct-light component resulting from the refractive index changes and turbulence factors in the atmosphere.

Synchronous measurements between the near and far receivers were not always achieved because of occasional difficulties with the PRC-10 communication sets (walkie-talkies) that were being used. Under those conditions it was often difficult to obtain the attenuation coefficient from the relationship

$$\frac{I_1 D_1^2}{I_2 D_2^2} = e^{-\sigma(D_1 - D_2)}$$

where I_1 and I_2 are the received signal intensities, D_1 and D_2 are the respective source-to-receiver distances, and σ is the effective attenuation coefficient between D_1 and D_2. Estimation of visual ranges in the field was then made, with a further check being obtained from the visibility reports at the Evans Signal Laboratory Weather Station about three miles south of the field station. Consideration of the relative sensitivities of the receivers at each location yielded sufficiently accurate attenuation coefficients during synchronous measurements. Field calibrations with a neon-glow-tube unit were made prior to and following the tests. Cloud-cover amounts and heights were estimated at the field station and further checked with the weather station.

During the night of 5 December 1960, the relative angular scattering effects of the aerosols were measured from about 5° to 140° with a nephelometer built by the Perkin-Elmer Corporation under a USASRDL contract.

RESULTS

Figure 3 is a block diagram of the receiver equipment. The noise level in the field was such that under clear skies with visibility greater than 20 miles, the brightness of the full moon, at about a 50° elevation, yielded a signal of the order of one volt under a maximum amplifier gain of 1000. Under the same conditions the interpolated signal level would have been more than 500 volts. Although the noise problem was insignificant, it was found that the receiver response to the neon calibrator unit generally varied from 1% to about 5% before and after the tests. During the last part of the test series, the variations became greater, making it necessary to check the photomultiplier voltage continuously. Steps will be taken to find the cause of these variations.

Table 1, from which the pertinent graphs were obtained, shows the overall results of the test series. Both H_1 and H_2 measurements (as defined in Table 1) were not always taken during a night run because of occasional equipment difficulties, and lack of accessibility to both receiver sites on snow-covered ground. Case 1 from Table 1, with the estimated visibility between two and four miles, was included as a special case wherein varying amounts of stratus cloud cover moved in the close vicinity of the light source so that an intermittent block of the direct beam occurred. This situation, of course, brought about a wide variation in the ratio of

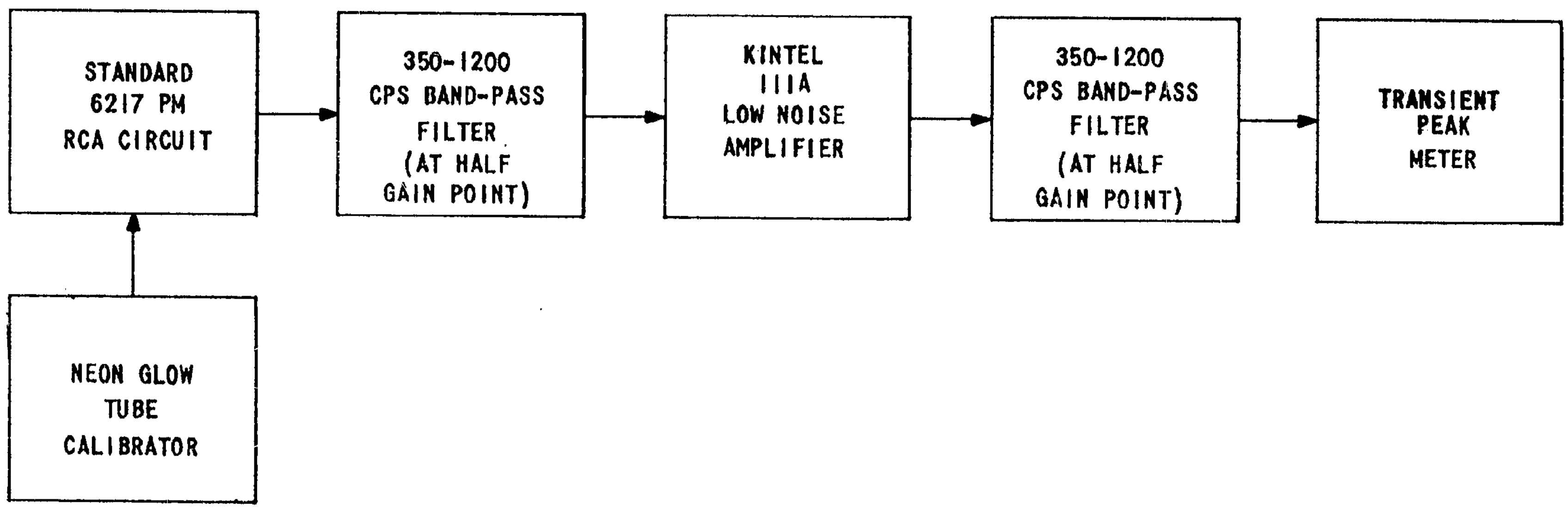

FIG. 13 BLOCK DIAGRAM OF FLASH TUBE RECEIVER

TABLE I

SUMMARY PERTAINING TO INDIRECT OR $\frac{\text{SCATTERED}}{\text{DIRECT}}$ RATIOS OF THERMAL RADIATION IN THE VISIBLE SPECTRUM

VISIBILITY	OPTICAL PATH	K_1	K_2	$K'_{180°/1}$	$K'_{180°/2}$	CLOUD AND/OR SNOW CONDITIONS	OTHER REMARKS
2-4 MILES	(CASE 1) σD_2 = 1.8		912, 99, 164% FOR 180° W		185%/W	VARYING, LOW WISPY STRATUS CLOUDS AT 4-600' ABOVE SEA LEVEL (SOURCE AT ~500' ABOVE SEA LEVEL). THIN STRATOCUMULUS OVERCAST ESTIMATED AT 1600'-2000'. NO SNOW PRESENT.	(1) ESTIMATED OPTICAL PATH. (2) $K'_{180°/2}$ MEASUREMENTS TAKEN WITHIN ABOUT 5 MINUTES OF EACH OTHER. (3) $K'_{180°/2}$ THEORETICAL VALUE ASSUMES UNLIMITED VISIBILITY.
	(CASE 2) σD_1 = 0.96 σD_2 = 1.6	88%/180°W AT ~2145 HRS 66%/180°G	202, 200, 183, 273%/180°W BETWEEN 2135-2100 HRS 102%/180°W 145%/180°B 114%/180°G 107%/180°R	53, 100, 120%/W BETWEEN 2200-2230HRS	70, 173%/W BETWEEN 2151-2226 HRS	~2" SNOW LAYER. 8-9/10 THIN STRATOCUMULUS BECOMING THICKER AND 10/10 TOWARDS END OF TEST BUT REMAINING TRANSLUCENT. CEILING ESTIMATE OF 2000'.	(1) MEASURED OPTICAL PATHS. (2) INCREASE OF $K_{180°W/2}$ BY ABOUT 35% IN ABOUT 2 HOURS AFTER INITIAL INCREASE OF 30% IN 45 MINUTES. (3) 227% INCREASE FOR $K'_{180°W/1}$ IN ABOUT 30 MINUTES (4) ALMOST 250% INCREASE FOR $K'_{180°W/2}$ IN ABOUT 25 MINUTES
4-6 MILES	(CASE 1) σD_1 = 0.70 σD_2 = 1.14	41%/180°W 33%/135°W 47%/135°B 21%/135°R 20%/90°W 25%/90°B 17%/90°R	61%/180°W 45%/135°W 79%/135°B 60%/135°G 41%/135°R 60%/90°B			CLEAR SKIES WITH NO SNOW.	(1) ESTIMATED OPTICAL PATHS. (2) POLAR SCATTERING MEASUREMENTS TAKEN NEAR BASE OF THE SOURCE. (3) SHARP TEMPERATURE INVERSION OF ABOUT 6°F BETWEEN GROUND AND 150' LEVEL MEASURED AT SOURCE SITE. (4) K_1 AND K_2 VALUES IN BRACKETS OBTAINED IN SEQUENCE.
	(CASE 2) σD_1 = 0.84 σD_2 = 1.42	73%/180°W 81%/180°W 71%/180°W 96%/180°B 87%/180°G 63%/180°R	170%/180°W 192%/180°B 111%/180°G 74%/180°R	14%/W 20%/B 13%/G 4%/R	33%/W 44%/B 20%/G 21%/R	1 DAY OLD SNOW ~4" AND 12" DEPTH IN SOME AREAS. SCATTERED HIGH CIRRUS CLOUDS.	(1) ESTIMATED OPTICAL PATH. (2) $K_1/180°W$ INCREASED FROM 73 TO 81% IN ABOUT 2 HRS. $K_2/180°W$ MEASUREMENTS MADE ONCE (3) RIME CRYSTALS FOUND ON OPAL GLASS AT END OF TEST AT D_2 SITE. (4) K_1 VALUES IN BRACKETS OBTAINED IN SEQUENCE.
6-8 MILES	(CASE 1) σD_2 = 0.81		65%/180°W			5 DAY OLD, HARDENED SNOW. CLEAR EXCEPT FOR HIGH, SCATTERED CIRRUS-TYPE CLOUDS.	(1) ESTIMATED OPTICAL PATH. (2) FT 503 GE FLASH TUBE USED. (3) HIGH PRESSURE (30.3") WITH VERY LIGHT SW WINDS.
	(CASE 2) σD_1 = 0.80	37%/180°W				NO SNOW. SCATTERED BECOMING HIGH BROKEN CLOUDS ABOVE 16000'.	(1) ESTIMATED OPTICAL PATH.
8-10 MILES	(CASE 1) σD_2 = 0.63		43%/180°W 60%/180°B 30%/180°R		12%/W 13%/B 0%/G 5%/R	2 DAY OLD SNOW. ~15" DEEP. 5-8/10 THIN, ALTOCUMULUS AT 8-10,000' BECOMING 3/10' STRATOCUMULUS AT 5-8000' AT TIME OF VERTICAL MEASUREMENTS.	(1) ESTIMATED OPTICAL PATH. (2) FT 503 GE FLASH TUBE USED.
	(CASE 2) σD_1 = 0.50	95%/180°W 59%/180°B 32%/180°R		8.8%/W 7.4%/B 6.5%/R		3-4 DAY OLD SNOW OF MORE THAN 12" DEEP. 8-10/10 THIN ALTOCUMULUS AT 8-10,000'	(1) ESTIMATED OPTICAL PATH.
10-15 MILES	(CASE 1) σD_2 = 0.63		20%/[illegible]			CLEAR SKIES. NO SNOW.	(1) ESTIMATED OPTICAL PATH. (2) SOME DISTANT HAZE NOTED FROM TOP OF TOWER IN LATE AFTERNOON.
	(CASE 2) σD_1 = 0.28 σD_2 = 0.43	17%/180°W 19%/180°B 13%/180°G 11%/180°R 15%/135°W 20%/135°B 13%/135°G 11%/135°R 12%/90°W 16%/90°B 11%/90°G 5%/90°R 10%/45°W 11%/45°B 3%/45°G 7%/45°R	19%/180°W 22%/180°B 14%/180°G 13%/180°R $K_{135°W}/K_{90°W}$ = 1.26 $K_{135°B}/K_{90°B}$ = 1.19 $K_{135°G}/K_{90°G}$ = 1.22 $K_{135°R}/K_{90°R}$ = 1.31 $K_{90°W}/K_{45°W}$ = 1.36 $K_{90°B}/K_{45°B}$ = 1.51 $K_{90°G}/K_{45°G}$ = 1.0 $K_{90°R}/K_{45°R}$ = 1.63	3-4%/W 5-6%/B 6%/G 4%/R		SCATTERED HIGH, THIN CIRROSTRATUS CLOUDS. SEVERAL INCHES OF SNOW PRESENT.	(1) MEASURED OPTICAL PATHS. (2) 60 MINUTES TIME DELAY BETWEEN $K_{180°W/1}$ AND $K_{180°W/2}$ MEASUREMENTS. (3) K PLOTTED AS A RESULT OF A MARKED LIGHT INTENSITY DROP WITH THE OCCULTER CONE MEASUREMENTS. OCCULTER UP MEASUREMENTS HANDLED FIRST; THESE VALUES WERE NOT PLOTTED ON GRAPHS.
	(CASE 3) σD_1 = 0.28 σD_2 = 0.46	41-45%/180°W AFTER ABOUT 2 HRS. 60%/180°B 22%/180°R 36%/135°W 51%/135°B 24%/135°R 34%/90°W 64%/90°B 28%/90°R 81%/45°W 99%/45°G 21%/45°R	59-77%/180°W AFTER ABOUT 2 HRS. 59%/180°W 76%/180°B 32%/180°R 71%/135°W 91%/135°B 17%/135°R 54%/90°W 66%/90°B 15%/90°R 51%/45°W 62%/45°B 90%/45°R	8.5-9%/W AFTER 2 HRS. 13%/B 4%/R START OF TEST	11-13%/W AFTER ABOUT 2 HRS. 21%/B 7-8%/R START OF TEST	8-10" SNOW. 8-10/10 ALTOSTRATUS/CIRROSTRATUS AT ~10,000'.	(1) MEASURED OPTICAL PATHS. (2) σ_W = 0.28/MILE, σ_B = 0.30/MILE, σ_R = 0.096/MILE. (3) K_1 VALUES FOR FIELDS OF VIEW OTHER THAN $K_1/180°W$ NOT PLOTTED. (4) K_2 VALUES FOR 135° FIELD OF VIEW, WITH RESPECT TO 180° VALUES, ARE QUESTIONABLE.
	(CASE 4) σD_1 = 0.30	21%/180°W				8-9/10 STRATOCUMULUS AT START OF TEST RAPIDLY DISSIPATING TO 1-2/10 BETWEEN 6-8000' TOWARDS END OF TEST IN ABOUT 1 HOUR. ABOUT 1" DEEP, 1 WEEK OLD SNOW.	(1) ESTIMATED OPTICAL PATH.
	(CASE 5) σD_1 = 0.24 σD_2 = 0.42	66%/180°W AT START OF TEST (8-9/10 SCu) 53%/180°B 30%/180°R	90%/180°W AT START OF TEST 87%/180°B 68%/180°R	11%/W 11%/B 8%/R	21%/W 21%/B 13%/R	MOSTLY 7-8/10 STRATOCUMULUS (SCu) AT 2-3000' WITH LITTLE NOTICEABLE CHANGE UNTIL ABOUT 10 MINUTES BEFORE END OF 1 HOUR TEST WHEN CLOUDS RAPIDLY DISSIPATED TO 1/10 AND THEN TO A TRACE. ABOUT 4 DAY OLD SNOW ABOUT 1' DEEP PRESENT.	(1) MEASURED OPTICAL PATHS (2) σ_W = 0.22/MILE AT START OF TEST σ_W = 0.12/MILE AT END OF TEST σ_B = 0.71/MILE, σ_R = 0.03/MILE: MEASUREMENTS TAKEN AFTER INITIAL σ_W MEASUREMENT WAS MADE
15-20 MILES	(CASE 1) σD_2 = 0.33		19%/180°W			10/10 MIDDLE CLOUDS ABOVE 10,000'. SOME SNOW.	(1) ESTIMATED OPTICAL PATH.
	(CASE 2) σD_2 = 0.33		28%/180°W			10/10 ALTOCUMULUS MIDDLE CLOUDS ABOVE 10,000'. 17" DEEP, 1 DAY OLD SNOW.	(2) ESTIMATED OPTICAL PATH FT 503 GE FLASH TUBE USED.
> 20 MILES	(CASE 1) σD_1 = 0.12 σD_2 = 0.19	10%/180°W	13%/180°W			CLEAR SKIES. NO SNOW.	(1) ESTIMATED OPTICAL PATH.
	(CASE 2) σD_1 = 0.12	9.5%/180°W				CLEAR SKIES. NO SNOW	(2) ESTIMATED OPTICAL PATH.

LEGEND:

K_1 = SCATTERED IN RADIATION WITH A 1.2 MILE DISTANT RECEIVER FACING THE SOURCE ÷ DIRECT RADIATION WITH THE RECEIVER FACING THE SOURCE

K_2 = SAME AS K_1 BUT APPLICABLE TO A 1.9 MILE DISTANT RECEIVER

K'_1 = SCATTERED IN RADIATION WITH A 1.2 MILE DISTANT RECEIVER FACING VERTICALLY UPWARD ÷ DIRECT RADIATION WITH RECEIVER FACING THE SOURCE.

K'_2 = SAME AS K'_1 BUT APPLICABLE TO A 1.9 MILE DISTANT RECEIVER

GENERAL NOTATION: $K_{(\text{FIELD OF VIEW})°W,B,G, \text{ OR } R/1 \text{ OR } 2}$ AND $K_{1 \text{ OR } 2}$ IN %/(FIELD OF VIEW)°W,B,G, OR R/1 OR 2.

WHERE W = WHITE OR UNFILTERED LIGHT; G = GREEN LIGHT

B = BLUE LIGHT; R = RED LIGHT

1 = D_1 = 1.2 MILE DISTANT RECEIVER; 2 = D_2 = 1.9 MILE DISTANT RECEIVER

the indirect to the direct light, i.e., the H_2 column.

Figure 1 compares the semiempirically derived relationships for a 180° receiver field of view, in the case of white light, of Stewart and Curcio and of Duncan with that of some of Gibbons' interpolated empirical results[3] and the author's empirical results, as well as the results of the theoretical calculations of Gibbons for a hazy atmosphere. The spectral sensitivity curves in Figs. 4 and 5 denote a broad region from about 3300Å to 7000Å, with the average wavelength being close to 5000Å. The average wavelength selected by the other investigators is in the vicinity of 5600Å and is expected to apply also to white light. In addition, a totally absorbing ground surface was assumed by the other investigators, giving k a value of 0.5, which would be somewhat less than in the author's cases where no surface snow was present. This would indicate that for a given optical path and field of view, the author's measurements of H should be somewhat higher than the others for similar cases of typical hazy atmospheres. This, however, was not the case for optical paths of less than 0.7 except for those situations involving Gibbons' empirically interpolated data for the Nevada desert area.

It is noteworthy that for optical paths lying between about 0.7 and 1.2, the author's H values are appreciably higher than Gibbons' empirically interpolated data from the Nevada desert area, and slightly higher than Gibbons' theoretical values. The large difference among the curves of Gibbons, Stewart and Curcio, and Duncan at the higher optical-path lengths, i.e., above about 0.7, can be attributed largely to the provision by Stewart and Curcio and by Duncan for no loss of scattered light once the scattered light falls within the detector's field of view. The overall differences between the empirical curves of the author and Gibbons can be largely attributed to aerosol size-distribution differences. Such differences could occur, since the latter's measurements were made over water and the Nevada desert area, while the former's were taken over land about three miles west of the Atlantic ocean.

Six and four pertinent points for the cases of clear skies without and with snow on the ground, respectively, plotted in Fig. 6, tentatively determine a limited relationship between H and the optical path. The following two empirical relations are both derived for a slightly to moderately hazy atmosphere under clear skies, no snow, about 60% bare tree coverage, and about 40% farm-type soil: (1) $H(\%) = 21.5e^{0.957\,\sigma D}$ where $0.6 \leq \sigma D \leq 1.14$ with a ±1% maximum error, and (2) $H(\%) = 6.8e^{2.77\,\sigma D}$ where $0.1 \leq \sigma D \leq 0.6$ with a maximum error of ±10%. The situation for clear skies with snow on the ground tentatively reveals a relation: $H(\%) = 6.8e^{2.77\,\sigma D}$; $0.6 \leq \sigma D \leq 1.0$, with a maximum error of ±10%.

It is particularly noteworthy that the slope of the curve for those situations involving the presence of snow remains relatively unchanged for optical paths of about 0.4 to 1.0, whereas for situations without snow cover, the slope for optical paths between about 0.6 and 1.1 is less steep. It is probable that the steeper slope for the case of snow may be due to the multiple reflection processes that become significantly effective as the optical path increases beyond a certain point. It is interesting to note that for small optical paths, i.e., less than about 0.6, the snow alone has a negligible effect on H, whereas a very rapid H increase occurs in the optical path range above 0.6 to about 1.2.

Figure 7 denotes a limited number of results for white light at a 180° field-of-view receiver where snow and/or clouds were present. From a comparison of Fig. 6 (interpolated) and Fig. 7, it is of particular interest that, in the case where the optical path is about 1.5, the H factor, in the presence of snow on the ground and low cloud cover at an altitude close to 2000 feet, could be as much as 3-1/2 times as great as for the case with the same optical path but with no snow and cloud-cover present. This situation is applicable at the receiver distance of two miles, with visibility at about four miles.

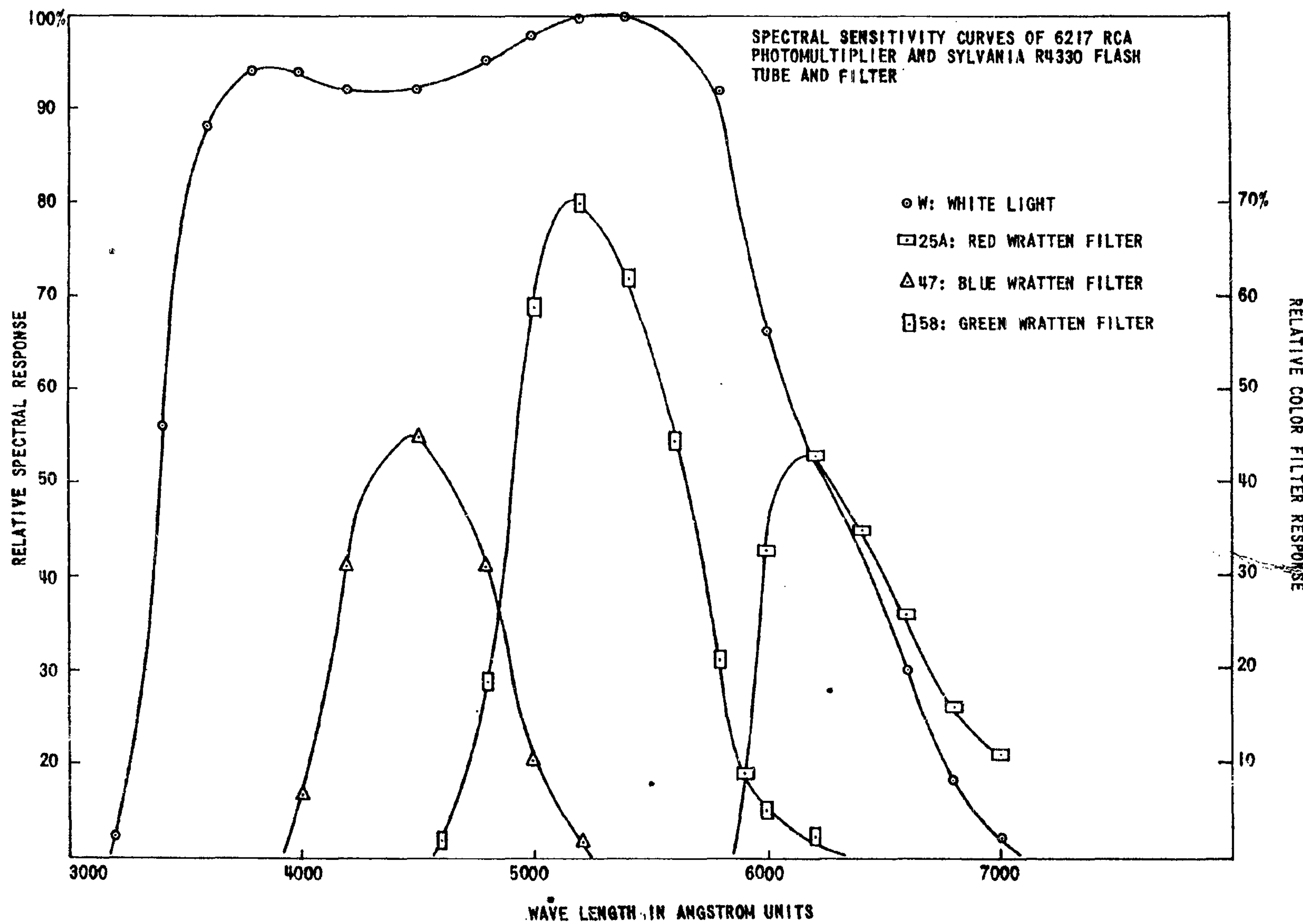

FIG. 4 SPECTRAL SENSITIVITY CURVES FOR SYLVANIA R4330 FLASH TUBE

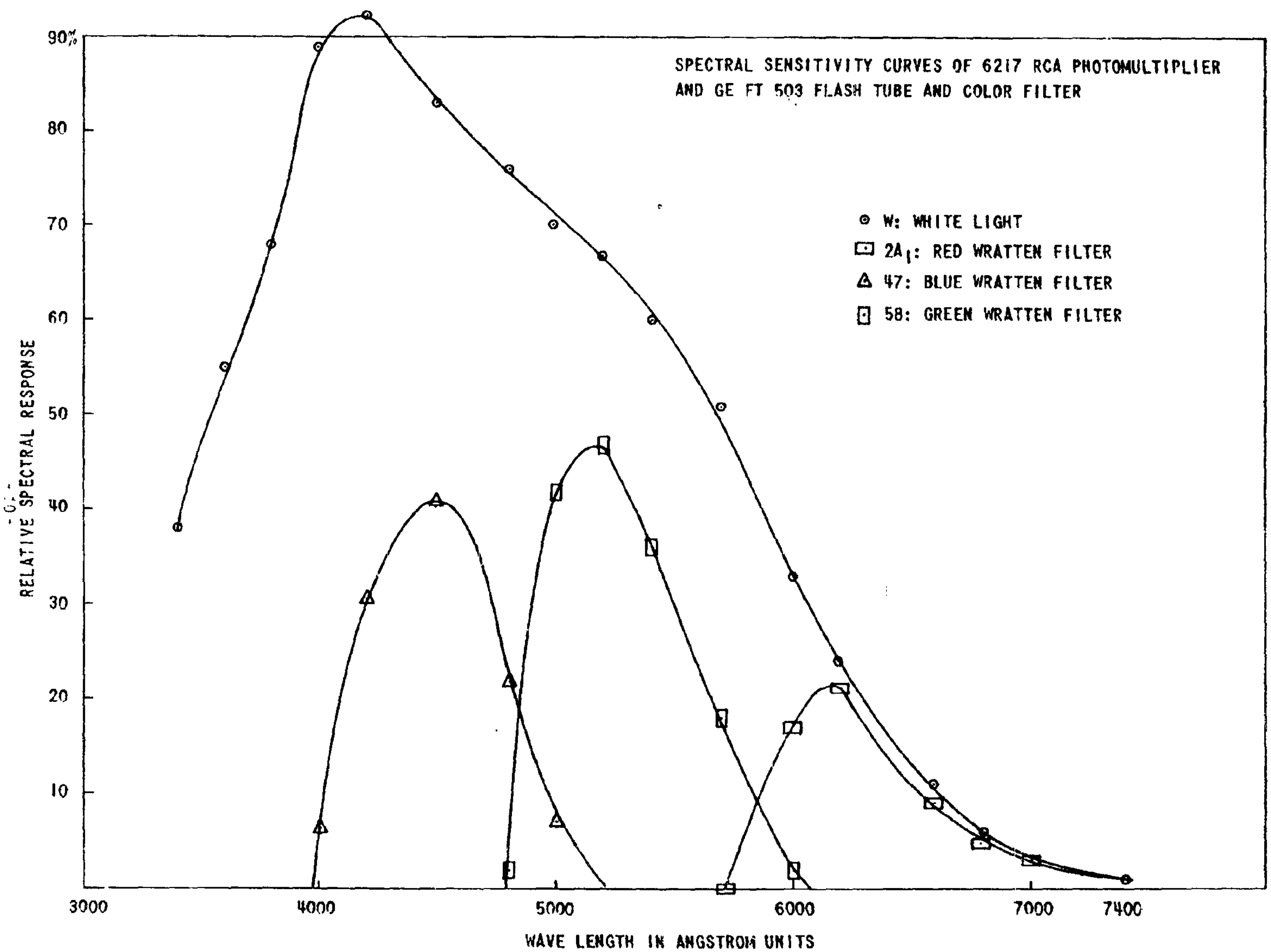

FIG. 5 SPECTRAL SENSITIVITY CURVES FOR GENERAL ELECTRIC FT 503 FLASH TUBE

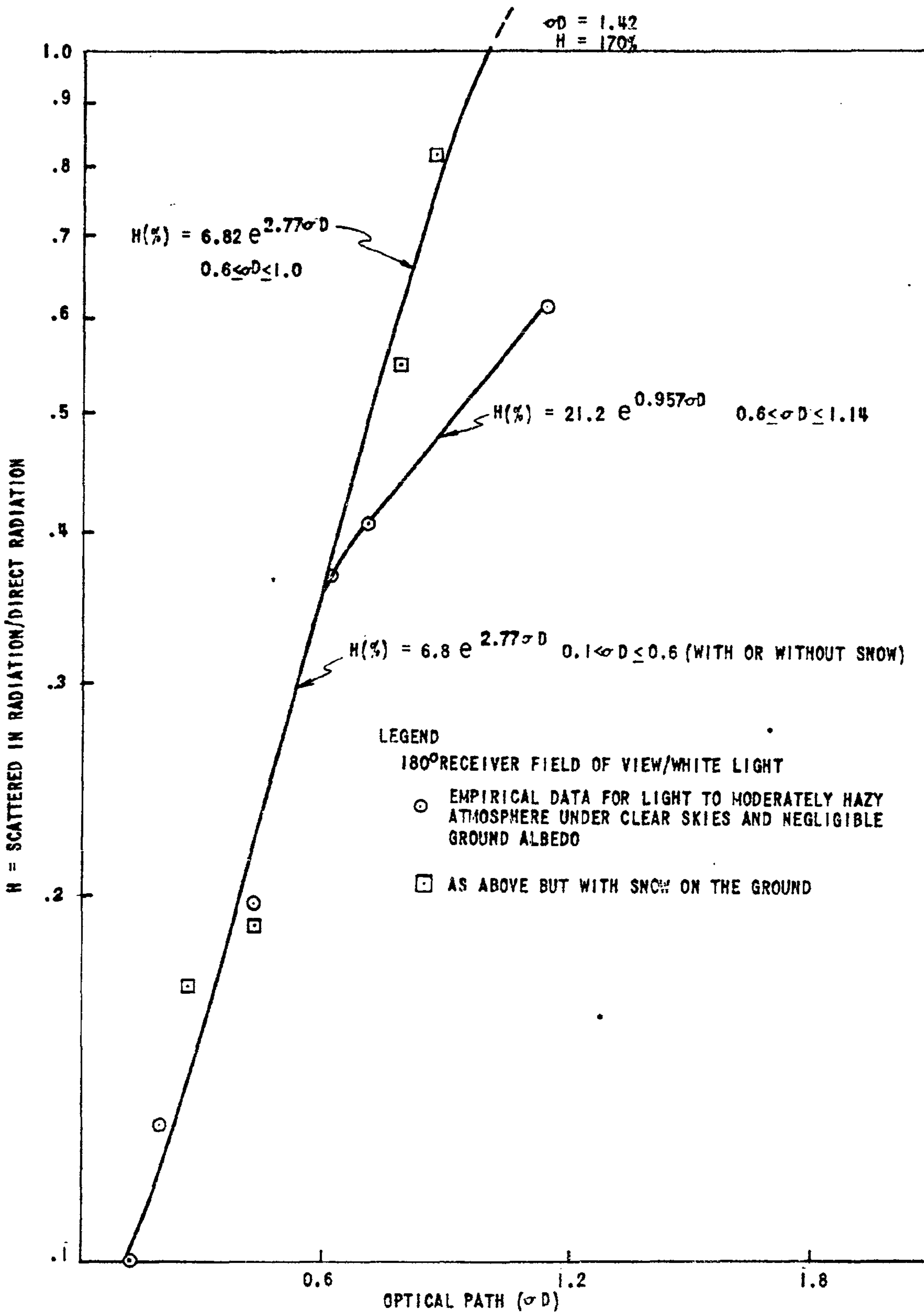

FIG. 6 H vs OPTICAL PATH, LIGHT TO MODERATE HAZY ATMOSPHERE, WITH AND WITHOUT SNOW

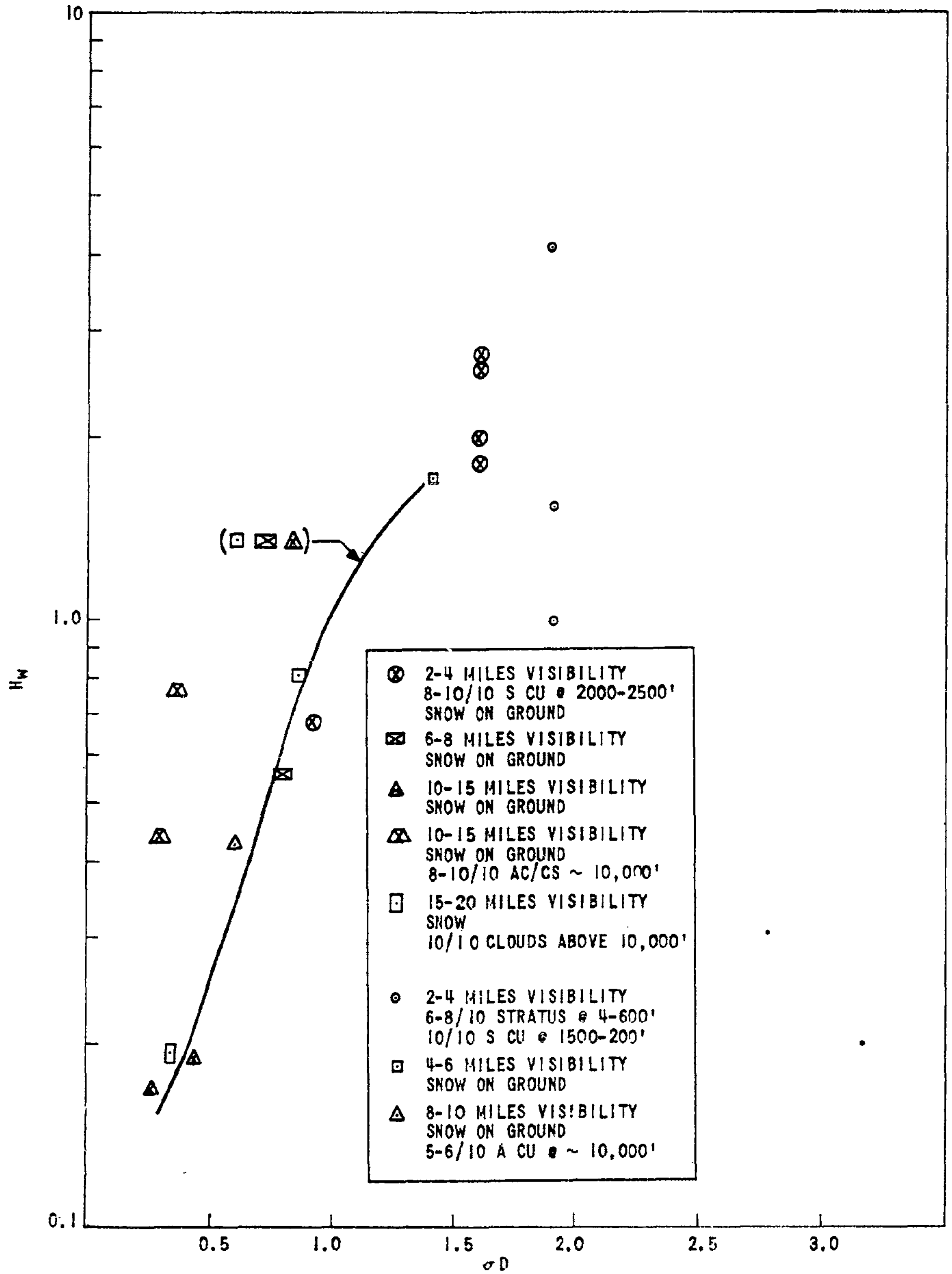

FIG. 7 H_W vs OPTICAL PATH WITH SNOW AND/OR CLOUDS PRESENT

Any sufficiently defined trend for determining an empirical relation H vs. σD for cases of snow and cloud coverage was not present because of lack of sufficient data. However, a curve is drawn through the points for the cases in Fig. 7 involving the presence of snow on the ground, which also reappears in Fig. 6.

Figure 8 shows the values of H vs. the optical path for different spectral regions at 180° field of view with snow and/or clouds present. This graph, however, was limited to only three weather situations. Lack of sufficient data in this direction, therefore, did not permit a tentative empirical relation to be derived. It is, however, interesting to note that H is greater for the blue region than for the green, and that H for the green is markedly greater than for the red. This tendency would be applicable for situations wherein the haze particles have a size distribution such that their effective radius is less than 0.5 micron, according to Mie's theory. This occurs since the Mie scattering coefficient then reaches a maximum for the blue light and a minimum for the red light.

A graph involving four weather situations of H' is shown in Fig. 9 where

$$H' = \frac{\text{scattered radiation, sensitive receiver plane pointing vertically skyward}}{\text{direct radiation, sensitive receiver plane pointing directly to the source}}.$$

It should be noted that situations can occur when the overhead scattered-thermal-radiation effects can be appreciably greater than the direct radiation effects, as indicated for the cases where the optical paths are 0.94 and 1.6 for the respective receiver distances of 1-1/6 and 2 miles in the presence of stratocumulus overcast at 2000 to 3000 feet, with snow on the ground. It is also evident that the H'_B (for blue light) is distinctly greater than H'_W (for white light) which, in turn, is distinctly greater than H'_R (for red light) except for the case where $\sigma D = 0.26$, with snow present and no effective cloud coverage.

Now two fundamental questions arise: (1) Where, or under what conditions, does multiple scattering occur in the lower atmosphere? (2) To what extent or degree does it occur? An attempt to answer these questions in some measure is now made with the application of reports by Bugnolo[7] and Guess.[8] Bugnolo shows that the multiple-scatter theory for an infinitely homogeneous and isotropic scattering medium, with a random distribution of scattering particles in the medium, is applicable in a given distance D whenever D is greater than 1.7 mean free paths. The probability that any incident ray is scattered n times in a distance $r \leq R$ is shown to be

$$P_n(r \leq R) = \frac{\sigma^n}{T(n)} \int_o^R r^{n-1} e^{-\sigma r} dr,$$

from which it follows that

$$P_1 = 1 - e^{-\sigma D} \qquad (1)$$

$$P_2 = 1 - (1 + \sigma D) e^{-\sigma D} \qquad (2)$$

$$P_3 = 1 - (1 + \sigma D) e^{-\sigma D} - \frac{(\sigma D)^2}{2} e^{-\sigma D}. \qquad (3)$$

Plots of these three relationships are shown in Fig. 10.

Indications of the extent to which multiple scattering occurs are based on the Guess[8] report wherein the diffuse reflection of point source radiation from a circular, horizontal Lambert plane onto a small flat receiver positioned in space above the plane is considered. Graphs and tables for determining the flux of point-source radiation reflected by the Lambert plane,

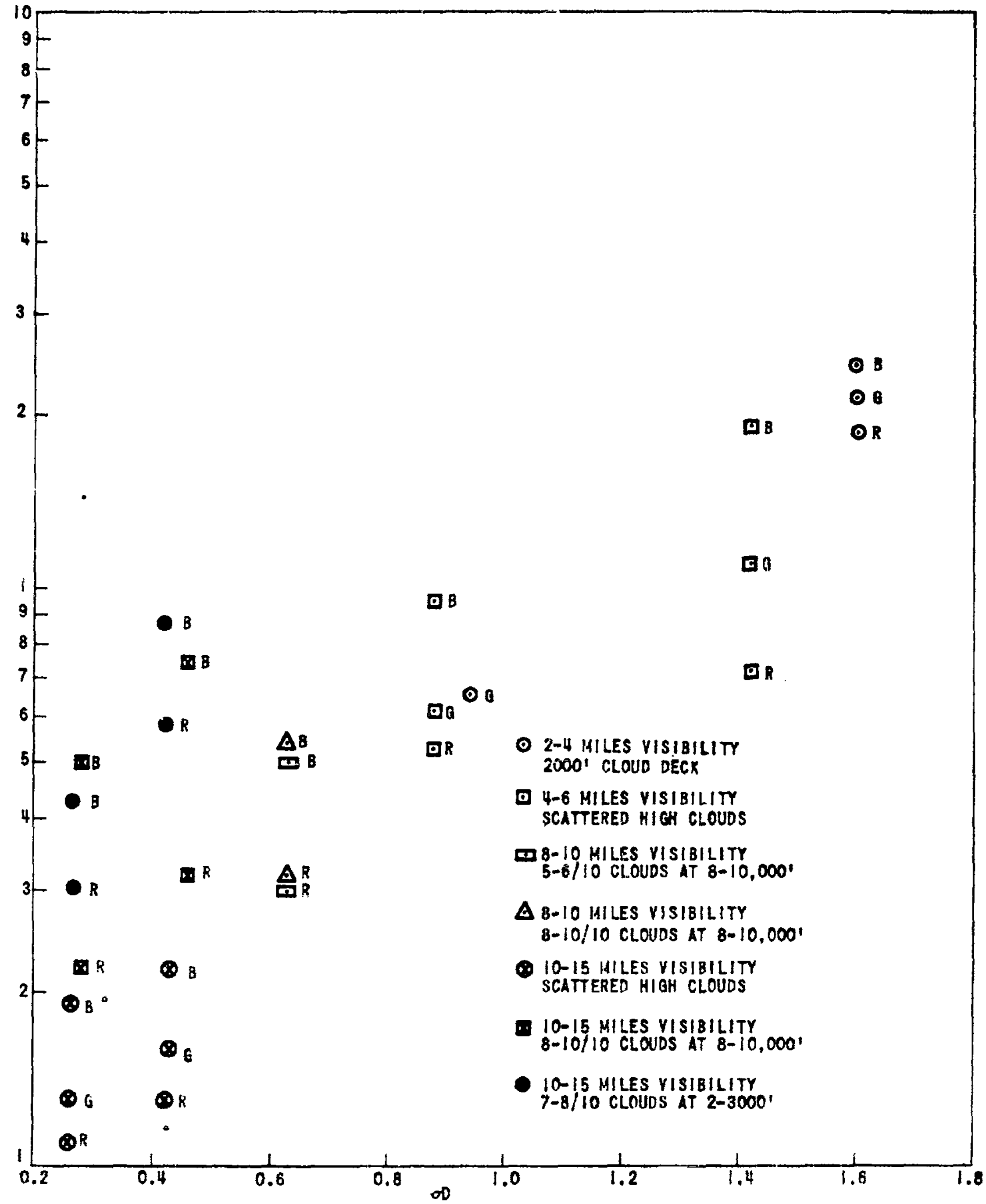

FIG. 8 H vs σD FOR DIFFERENT SPECTRAL REGIONS AT 180° FIELD OF VIEW WITH SNOW COVER
B=BLUE, G =GREEN, R=RED

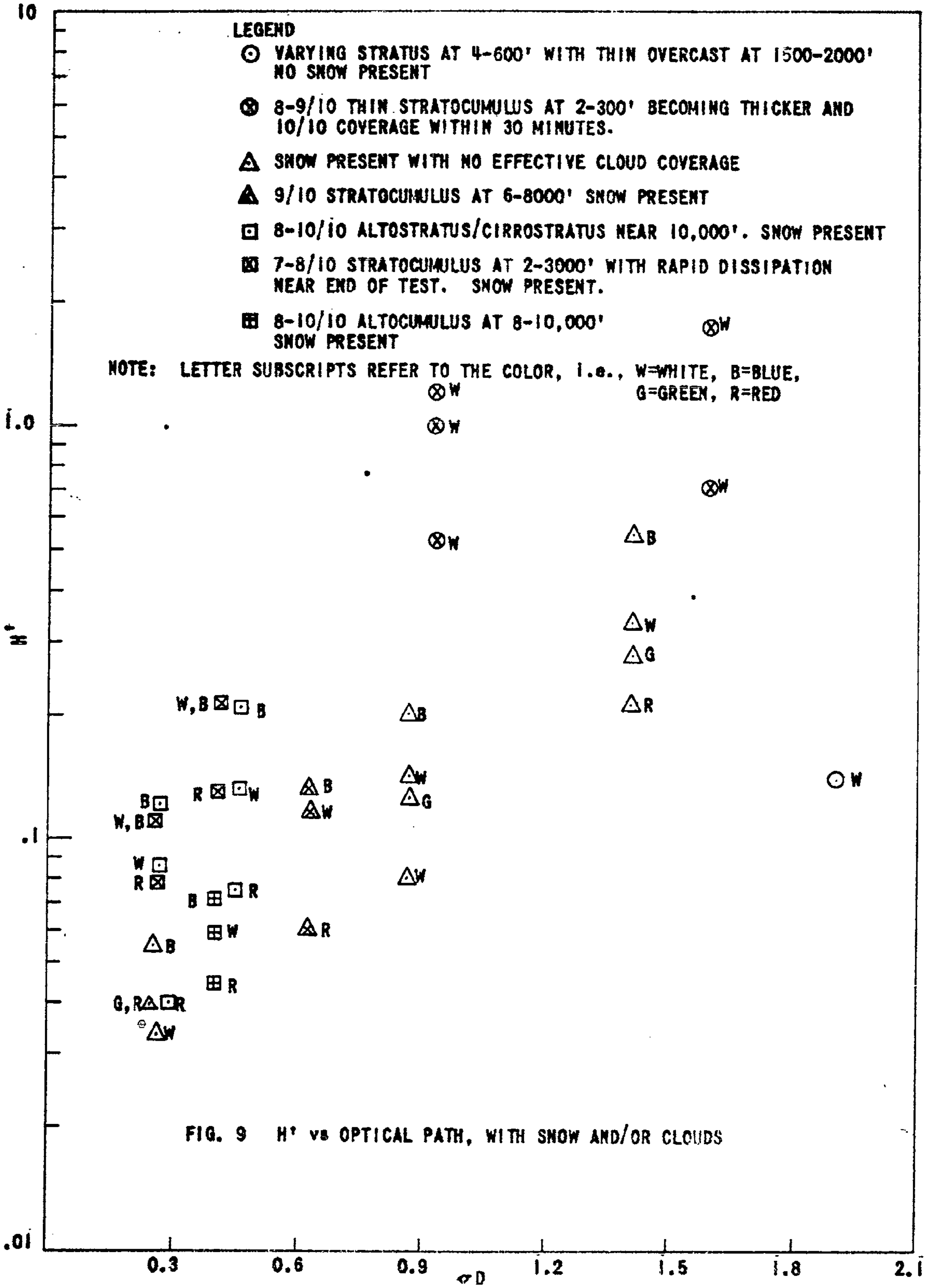

FIG. 9 H' vs OPTICAL PATH, WITH SNOW AND/OR CLOUDS

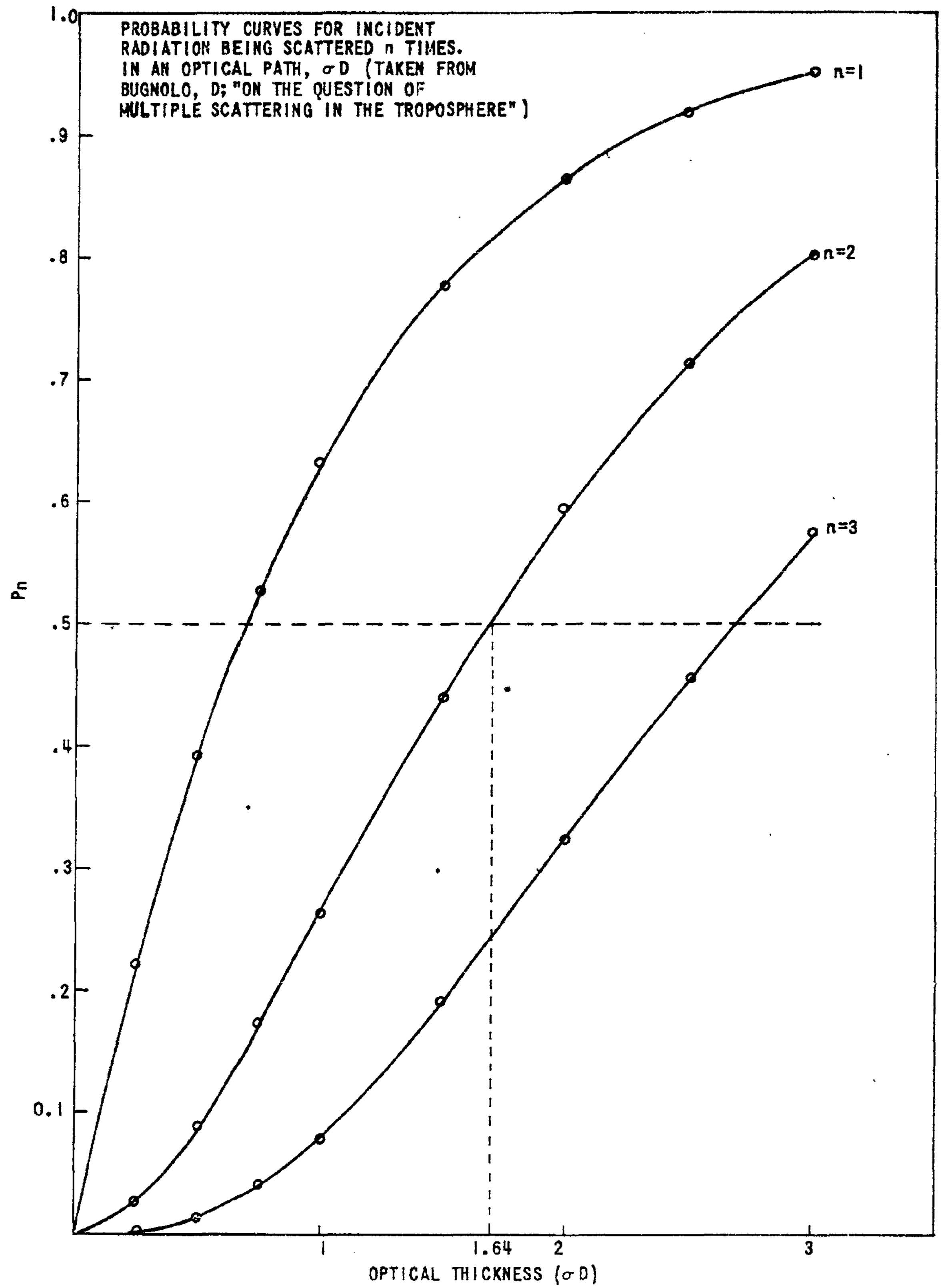

FIG. 10 PROBABILITY CURVES FOR SINGLE AND MULTIPLE SCATTERING

assuming no intervening atmospheric attenuation, are available for various Lambert disc radii and spatial positions of the receiver. Calculations of H' were determined from the relationship

$$H' = \gamma = \rho a \sigma' = \text{constant} \left(\frac{\rho E \alpha}{h^2}\right),$$

where α is a function of $(\frac{r_o}{h}, A_1, S_1)$ and $\sigma' = \text{constant}\left[S_1^2 + (A_1 - 1)^2\right]$, E = source intensity, and ρ = Lambert plane albedo. Here, r = radius of the Lambert plane; h = height of the source above the Lambert plane (in the case of cloud cover, with the receiver pointing vertically upward or towards the source in this report, h would be the height below the cloud deck); $A_1 = \frac{A}{h}$, where A = receiver altitude with respect to the Lambert plane; and $S_1 = \frac{S}{h}$, where S = receiver ground zero distance as denoted in Fig. 11. Graphs are also available for certain cases where the receiver is tilted relative to the Lambert plane. Here it is shown by Guess that $Q_R = \frac{\text{constant } \rho E_1 \times \alpha}{h^2}$, but where α is also a function of the direction cosines of the normal to the receiver.

Figures 12 and 13, showing the relationship between H and H' vs. cloud height for the geometry involved in these tests, are obtained through multiple interpolations from the A_1, S_1 data available from the Guess report, where r_o/h is taken as infinity and ρ as unity. The maximum of H in Fig. 12 occurs when the cloud deck is about one-third the detector ground-zero distance, and the curve for the 10,000-ft. ground-zero detector is appreciably broader in the vicinity of the peak. The empirical values included in the figure indicate the predominating effects of aerosol scattering effects, which are not considered in the Guess report. It can be surmised that for a very clear atmosphere the contribution to H from the snow reflections is, for all practical purposes, zero.

The relationship between H' vs. cloud height, as shown in Fig. 13, denotes the peak occurring at a cloud height approximately one-half the detector ground-zero distance, with a particularly broad peak occurring for the 10,000-ft. ground-zero detector. The attenuation factor due to the presence of aerosol causes appreciably lower empirical H' values.

Employing Fig. 10, where applicable, and Figs. 6, 12, and 13, it is possible to deduce the albedo effects of snow and/or clouds in the overall scattering effects at the receiving area. The following procedure is adopted, therefore, and the following cases considered:

(1) H vs. clear skies with snow on the ground with a single scattering-type optical path of $(\sigma D)_A$, empirical.

(2) H vs. clear skies with no snow on the ground for the same optical path as in (1); i.e., $(\sigma D)_A$, empirical.

(1) – (2) = (3) H vs. snow on the ground, assuming single type, independent, or incoherent scattering processes, i.e., contribution to H from surface snow.

(4) H vs. (cloud height)$_1$ with no aerosol attenuation between the snow and cloud cover, theoretical.

(5) H vs. (cloud height)$_1$ with snow for an optical path of $(\sigma D)_A$ between the snow and cloud covers, empirical (since there are no appropriate cases of H vs. cloud overcast with no snow on the ground).

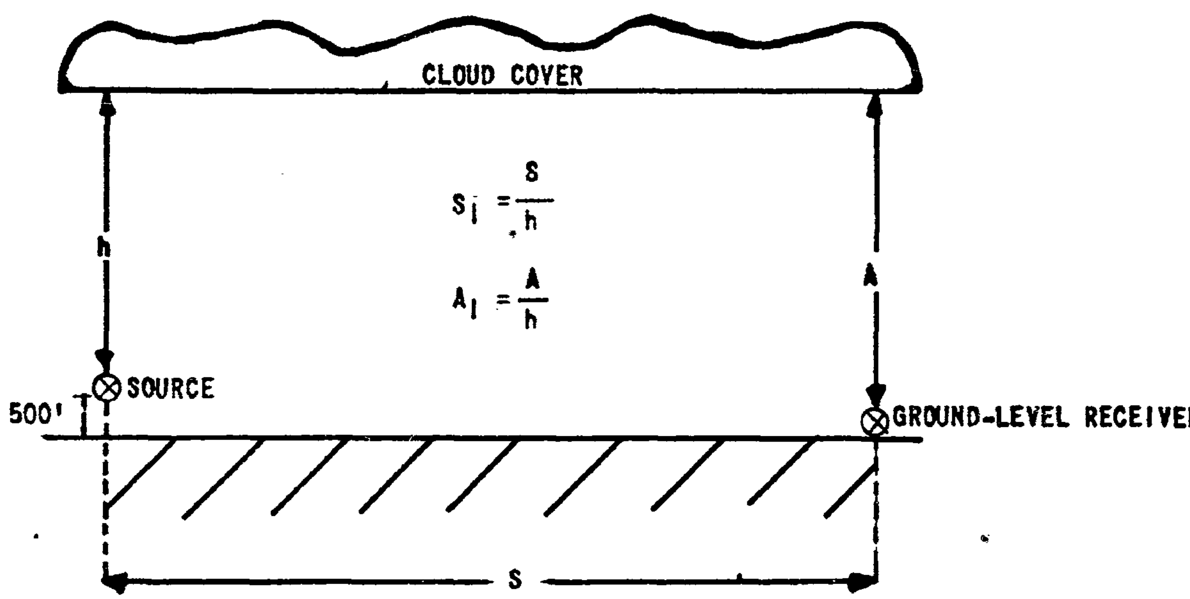

FIG. 11 PARAMETERS FOR H and H' THEORETICAL CALCULATIONS IN THE PRESENCE OF CLOUDS

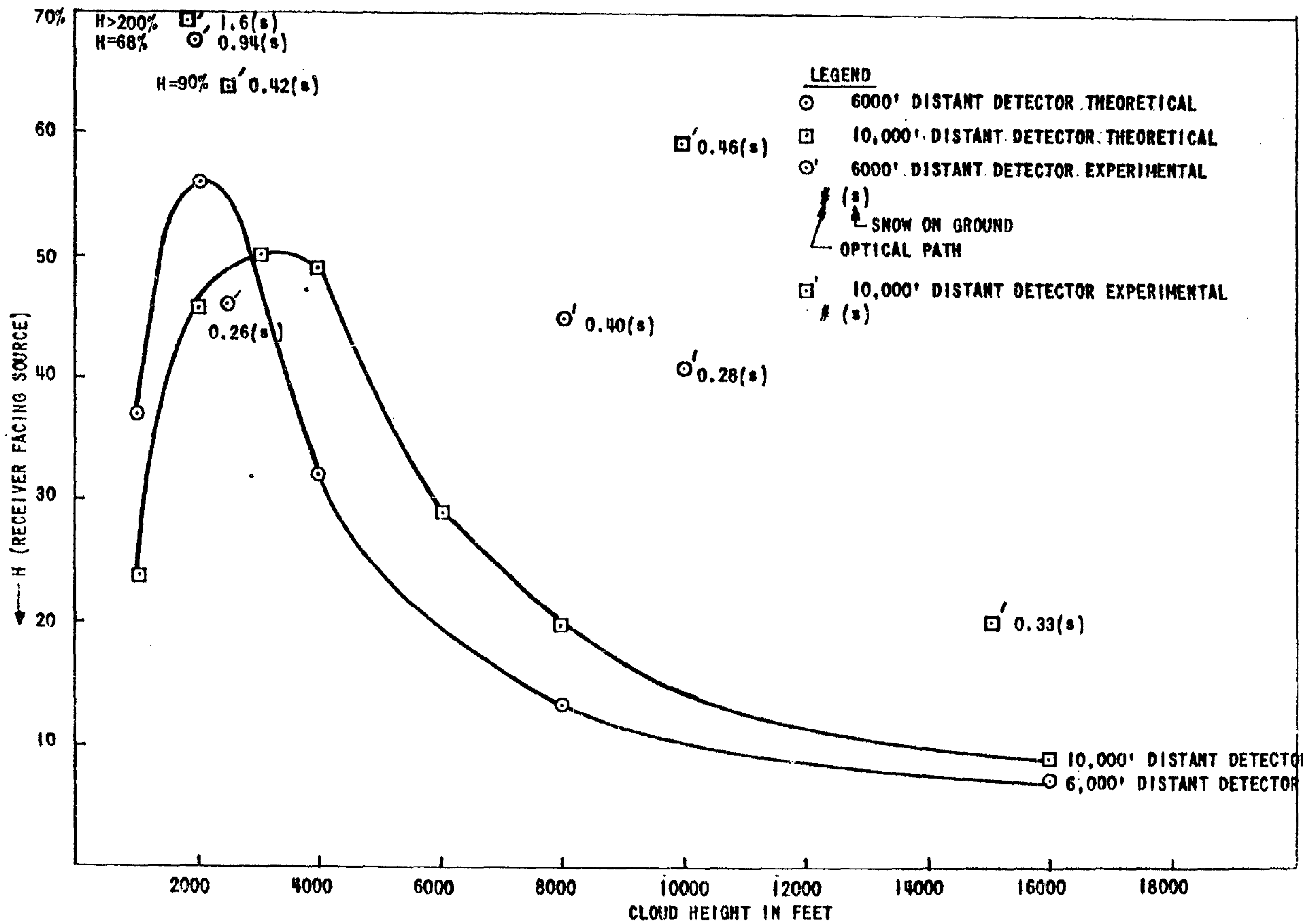

FIG.12 H vs CLOUD HEIGHT, THEORETICAL, ASSUMING A CLOUD ALBEDO FACTOR OF UNITY AND NO ATMOSPHERIC ATTENUATION.

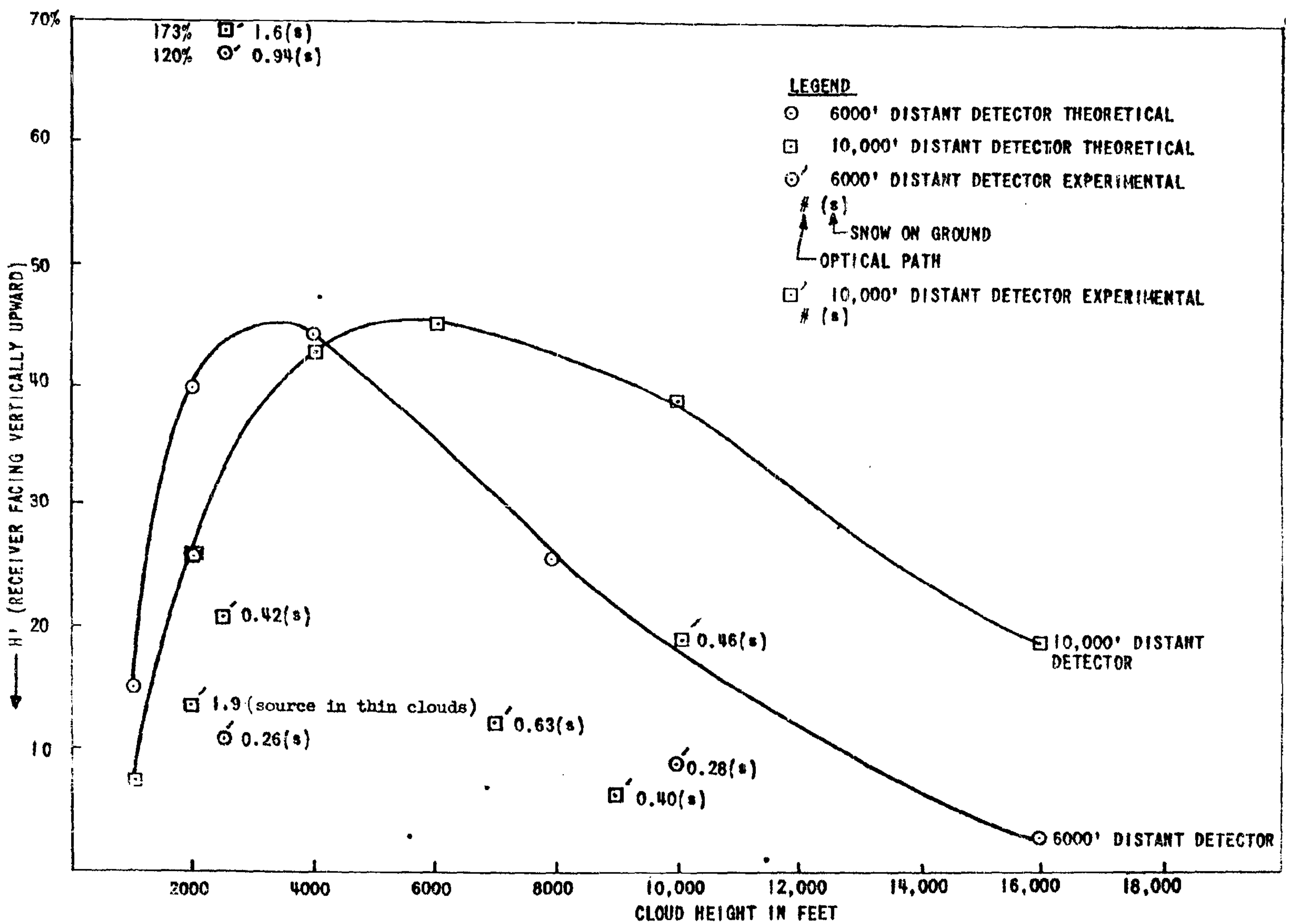

FIG. 13 H' vs CLOUD HEIGHT, THEORETICAL, ASSUMING A CLOUD ALBEDO FACTOR OF UNITY AND NO ATMOSPHERIC ATTENUATION.

(5) – (3), subtracting the effects of the snow, = (6) albedo effect of the cloud deck at a given height, i.e., 1, with an optical path of $(\sigma D)_A$, assuming both single type, independent aerosol scattering in $(\sigma D)_A$, and a Lambert-type reflecting cloud boundary.

Subtracting (4) from (6) yields (7), i.e., effects of aerosol scattering alone for $(\sigma D)_A$.

(8): $\frac{(7)}{(4)}$ x 100 = percent contribution of

$$\frac{\text{aerosol scattering between the surface and clouds in a given optical path of } (\sigma D)_A}{\text{cloud overcast albedo effect at a given height.}}$$

And similarly for H':

(9) H' vs. cloud height, no snow, optical path of $(\sigma D)_A$, empirical.

(10) H' vs. cloud height, with snow, optical path of $(\sigma D)_A$, empirical.

(9) – (10) → (11) H' contribution from the snow albedo effect alone for an optical path of $(\sigma D)_A$, empirical.

(12) H' vs. cloud height, no aerosol attenuation in the atmosphere below the cloud deck, with the clouds acting essentially as a Lambert reflector, theoretical.

(12) – (9) → (13): –H' from single scattering processes below the cloud deck; that is, $H'_{theoretical}$ is reduced by some factor –H'.

(14): $\frac{(13)}{(12)}$ x 100 = percent diminution of $H'_{theoretical}$ (from the cloud deck albedo effect) as a result of aerosol single, independent scattering processes below the cloud deck.

In such cases involving aerosol multiple nonindependent scattering processes, i.e., where the optical path σD is equal to or greater than 1.64, nonlinear effects present difficulties that do not permit a simple analysis as above. However, it can be expected that the overall effects of multiple scattering would bring a further increase in both H and H' as compared to the single scattering cases.

The case involving an estimated optical path of 1.9, with varying wispy stratus at 400 to 600 feet and an overcast at 1500 to 2000 feet, is taken as the only available situation where the probability of more than single-type aerosol scattering (i.e., twofold scattering) is greater than 0.5, as indicated from Fig. 10. Computations are limited to where the receiver is pointing vertically upwards, i.e., H' 180°_2, because of the variability of the stratus clouds between the source and receiver.

The results of such computations show that for a cloud base of 2000 feet with an assumed albedo factor ρ of 0.7, H' = 18%; and for $\rho = 0.6$, H' = 15%. This is rather close to the 14% empirical value obtained, and is noteworthy in view of the fact that the theoretical value is applicable for unlimited visibility, and yet it closely corresponds in value for the empirical situation where the estimated visibility is 3 miles and the optical path, 1.9. The indication here is that multiple scattering of a twofold type between the source and cloud deck and then between the cloud deck and receiver has a predominating effect, since the optical thickness is greater than 1.64. The high H' value for H' 180°_2, however, for case 2 (from Table 1) at an optical path of 1.6 and 2 to 4 miles visibility, with about a 2000-ft.-high cloud deck, would, in effect, discount the above conclusions on the grounds that the variable stratus had too much of an effect on lowering the H' value by its direct blocking effects.

Case 2, with a measured optical path of 1.6 and 2 to 4 miles visibility, is a borderline case for a 0.5 probability of the occurrence of a twofold type of scattering. With the snow on the ground as the Lambert plane, and then with the clouds considered separately as the Lambert plane, theoretical calculations for H indicate that the predominating scattering contributions are due to effects between a single and twofold type of aerosol forward scattering occurring in the general region between the cloud deck and the snow cover.

The following two conclusions can be drawn from Fig. 6 concerning the albedo effect of snow on the additional contribution to H. Firstly, below an optical path in the vicinity of 0.6 there seems to be no, or negligible, contribution to H as a result of the presence of snow on the ground. Secondly, above a 0.6 optical path, the albedo contribution of the snow seems to increase most rapidly in the optical-path region of about 0.8 to 0.9 and less rapidly from about 0.6 to 0.8 and 0.9 to about 1.0; i.e., (figures are approximate) a 15% increase for an optical path of 0.7, a 20% increase for an optical path of 0.8, a 60% increase for an optical path of 0.9, and an 80% increase for an optical path of 1.0.

In a similar vein, the following conclusions can be drawn from Fig. 12 concerning the albedo effects of a cloud deck on H, assuming a cloud albedo factor of 0.7 for the stratocumulus and 0.6 for the altocumulus and altostratus type, and taking into account the negligible contribution of the snow for optical paths of less than about 0.6. For the case where the optical path is 0.26 with the cloud height in the vicinity of 2500 feet, the $H_{empirical}$ value of 46% is lower than the $H_{theoretical}$ value of about 54%. This may be due to the fact that about an 80% cloud coverage of the sky was observed, with noticeable breaks in the vicinity of the source and receiver. In the case where the optical path is approximately 0.42 with approximately a 2500-ft. cloud height, the aerosol (that is, between the cloud deck and ground) contribution is near 14%. The contribution of $\frac{\text{aerosol scattering}}{\text{cloud albedo effect at 2500 feet}} = 30\%$. For the case of the optical path of 0.40 with about an 8000-ft. cloud height, the aerosol contribution is near 14%. The ratio of

$$\frac{\text{aerosol scattering}}{\text{cloud albedo effect at 8000 feet}} = 100\%.$$

For the case of the optical path of 0.28 with about a 10,000-ft. cloud height, the aerosol contribution is near 15%. The ratio of $\frac{\text{aerosol scattering}}{\text{cloud albedo effect}} = 150\%$. For the case of the optical path of 0.46 and 10,000-ft. cloud height, the aerosol contribution is near 22%. The ratio of

$$\frac{\text{aerosol scattering}}{\text{cloud albedo effect}} = 148\%.$$

For the case of an optical path of 0.33 with about a 15,000-ft. cloud height, the aerosol contribution is near 3%. The ratio of $\frac{\text{aerosol scattering}}{\text{cloud albedo effect}} = 33\%$.

Consideration is now given to those cases where the receiver is pointed vertically upwards so that its sensitive plane is parallel to the clouds. Similar reasoning as above can be employed to arrive at the percentage diminution of $H'_{theoretical}$ as a result of aerosol-single-scattering processes occurring between the ground and clouds. Such results, however, require empirical data on H' vs. cloud height, with no snow on the ground. If, however, one assumes that the effects of the snow for those cases indicated in Fig. 13 (where the optical path is less than 0.6) have a negligible contribution towards H', then the percentage diminution of $H'_{theoretical}$ from the cloud albedo effect as a result of aerosol single-type scattering may be determined for five cases. For example, in the case where the optical path is 0.26 and the cloud height is 2500 feet, the diminution of H' is $\frac{26 - 11}{26} \times 100 = 58\%$. Other cases show the following diminution:

Optical Path	Cloud Height	Percent Diminution
0.42	2,500 feet	0
0.40	9,000 feet	71
0.28	10,000 feet	53
0.46	10,000 feet	47

Because of the lack of data, no attempt has been made to arrive at an empirical relationship for the above type of cases.

Figures 14 through 17 present the effects of fields of view of the receiver for various regions of the spectrum. Insufficient data at this time, however, preclude any attempts for the derivation of empirical relationships, although it can be stated that for greater optical paths (while the other factors remain the same) the H factor drops more rapidly with a diminishing field of view. H is also greater for the smaller wavelengths; i.e., the blue region shows greater values than the green or red regions.

Figure 18 shows the polar-scattering curves obtained on the night of 5 December 1960, as a result of three independent measurements taken with a polar nephelometer near ground level in the vicinity of the source. Such curves obtained with white light indicate the relative volume scattering effects from about 5° to 140° with respect to the incident direction. This could permit a theoretical check of the determination of H for various fields of view. In addition, the slopes of these curves could serve as an indication of relative effective size distribution for a given aerosol concentration, assuming negligible change in the refractive indices of the prevailing aerosols. Concentration changes can also be noted from the curve displacements versus time.

CONCLUSIONS

Results of the tests, discussed in this report, indicate and support the feasibility of obtaining representative empirically established relationships involving the dependence of the ratio of scattered to direct visible radiation versus the optical path, under restricted weather conditions. For example, in the case of slightly to moderately hazy atmospheres, under clear skies and no snow, the relation H (in %) = $21.5\ e^{0.957\ \sigma D}$, where $0.6 \leq \sigma D \leq 1.14$, and the relation H (in %) = $6.8\ e^{2.77\ \sigma D}$, where $0.1 < D \leq 0.6$, are shown to prevail with a possible maximum error of ±10%. Furthermore, for a similar weather situation, but with snow-covered ground, the above relation changes to H (in %) = $6.8\ e^{2.77\ \sigma D}$, where $0.6 \leq \sigma D \leq 1.0$.

The presence of clouds (although not having a predominant effect in all cases, with one possible exception, on the overall scattering intensity at the detector) can be responsible for a significant percentage of the total scattered light.

It is also feasible, in the presence of predominating atmospheric single-scattering processes and assuming cloud and snow boundaries to behave effectively as Lambert reflectors, to determine the separate contributions to the $\frac{\text{scattered}}{\text{direct}}$ radiation from the intervening aerosols, the cloud deck, and the snow cover.

Much more data are necessary to establish an empirical relationship in the case involving the presence of clouds and/or snow. In addition, further data are necessary to substantiate the above-mentioned relationships arrived at empirically under restricted weather situations, as well as to expand such tests to cover a greater variety of weather patterns.

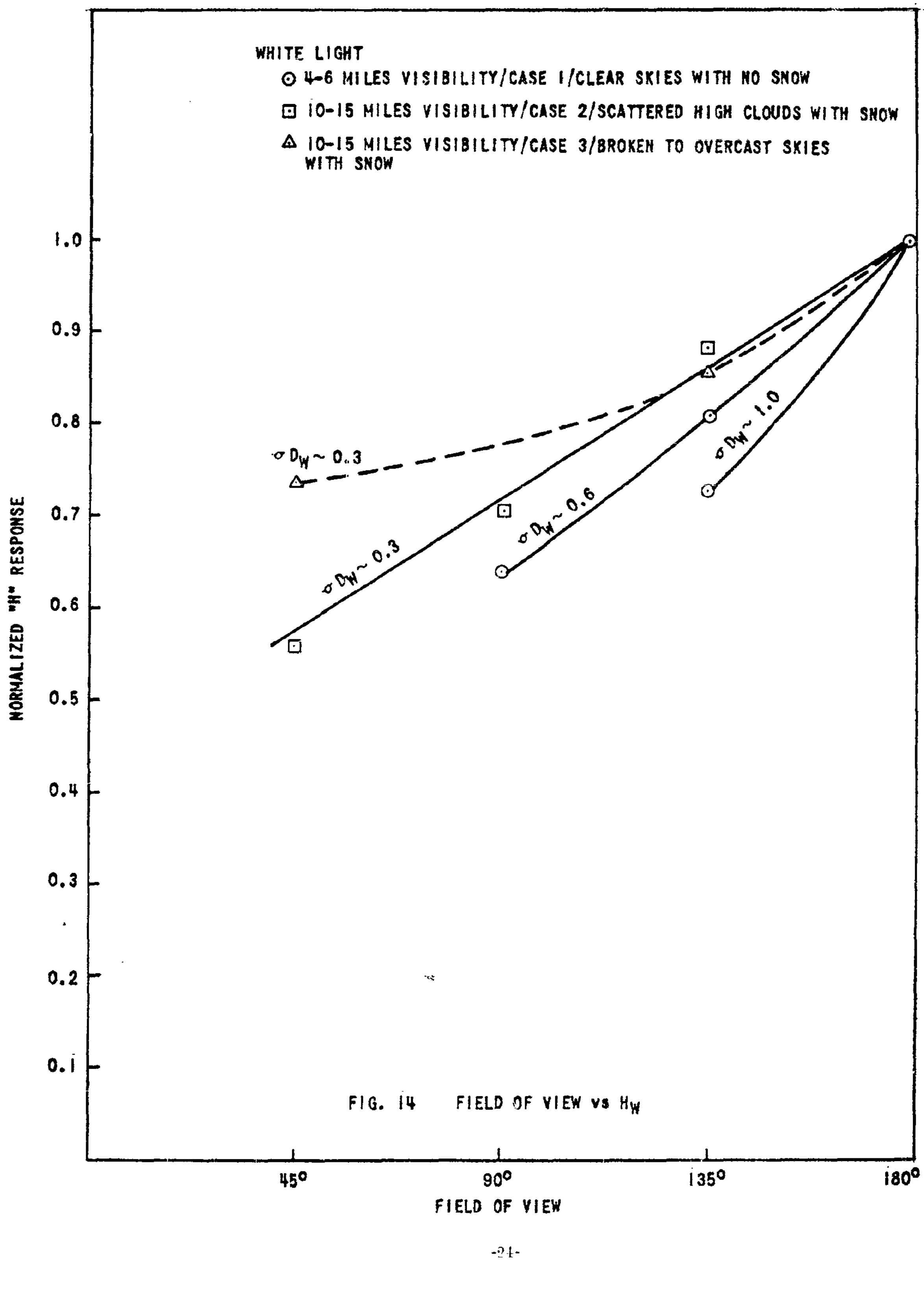

FIG. 14 FIELD OF VIEW vs H_W

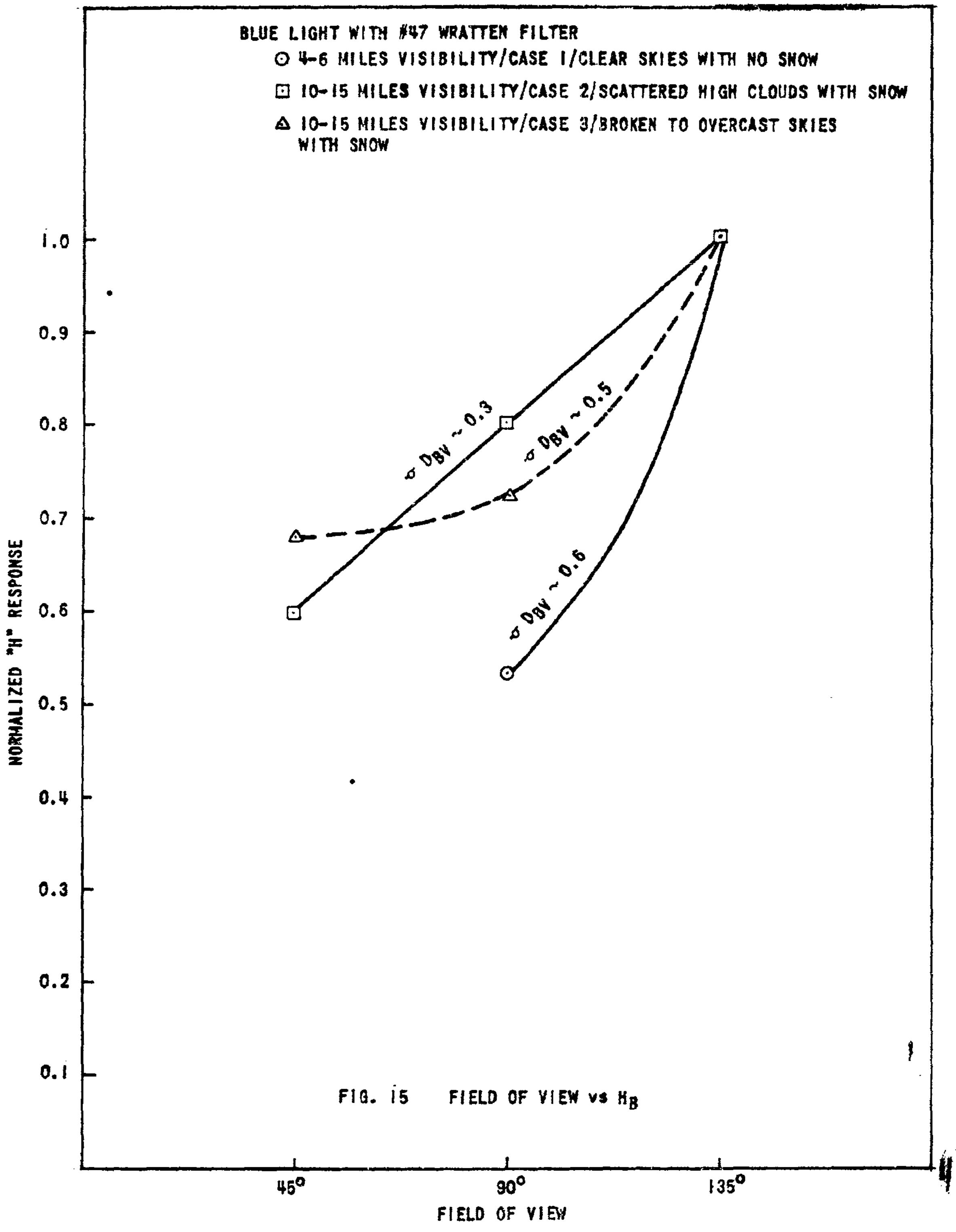

FIG. 15 FIELD OF VIEW vs H_B

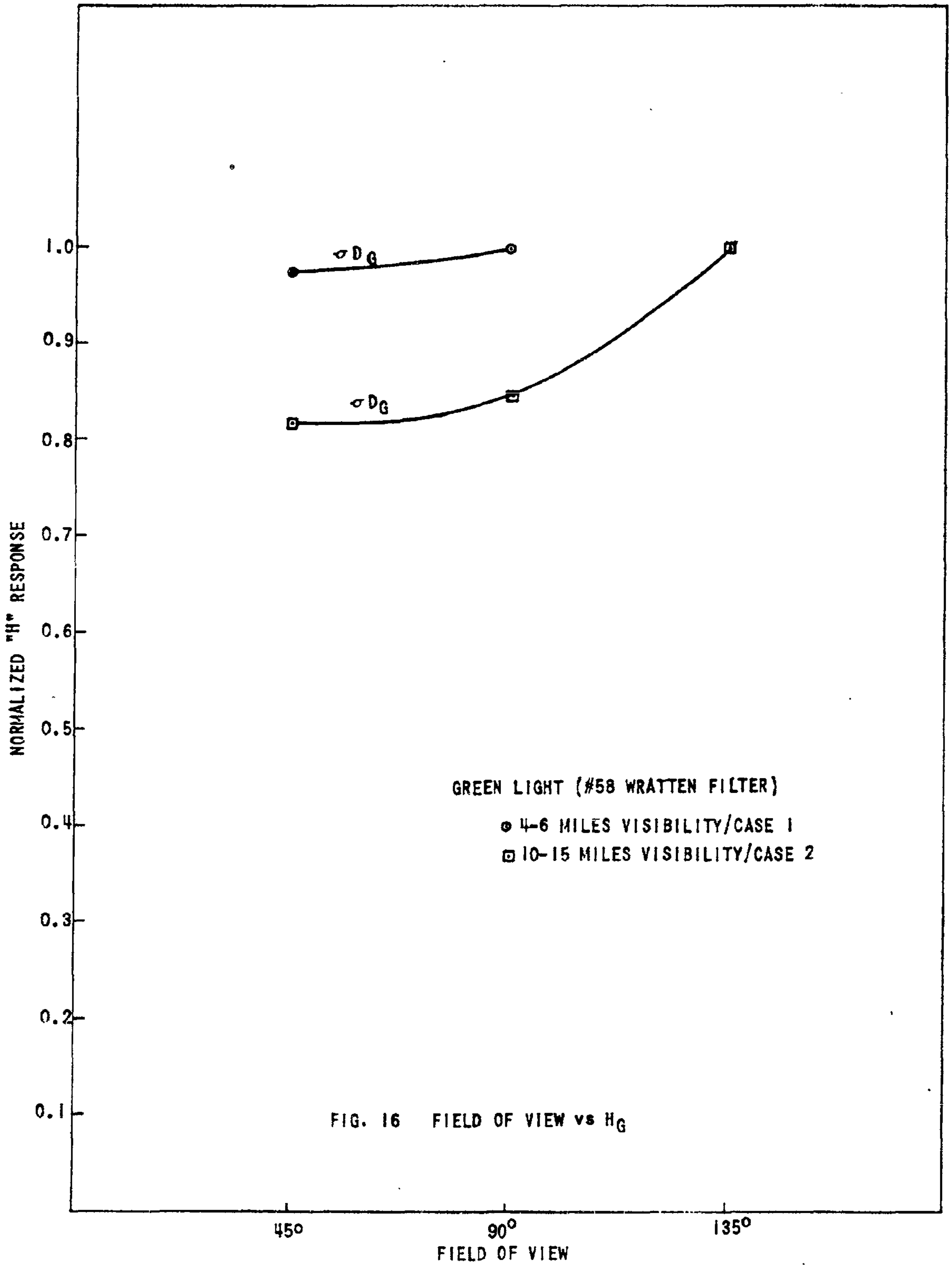

FIG. 16 FIELD OF VIEW vs H_G

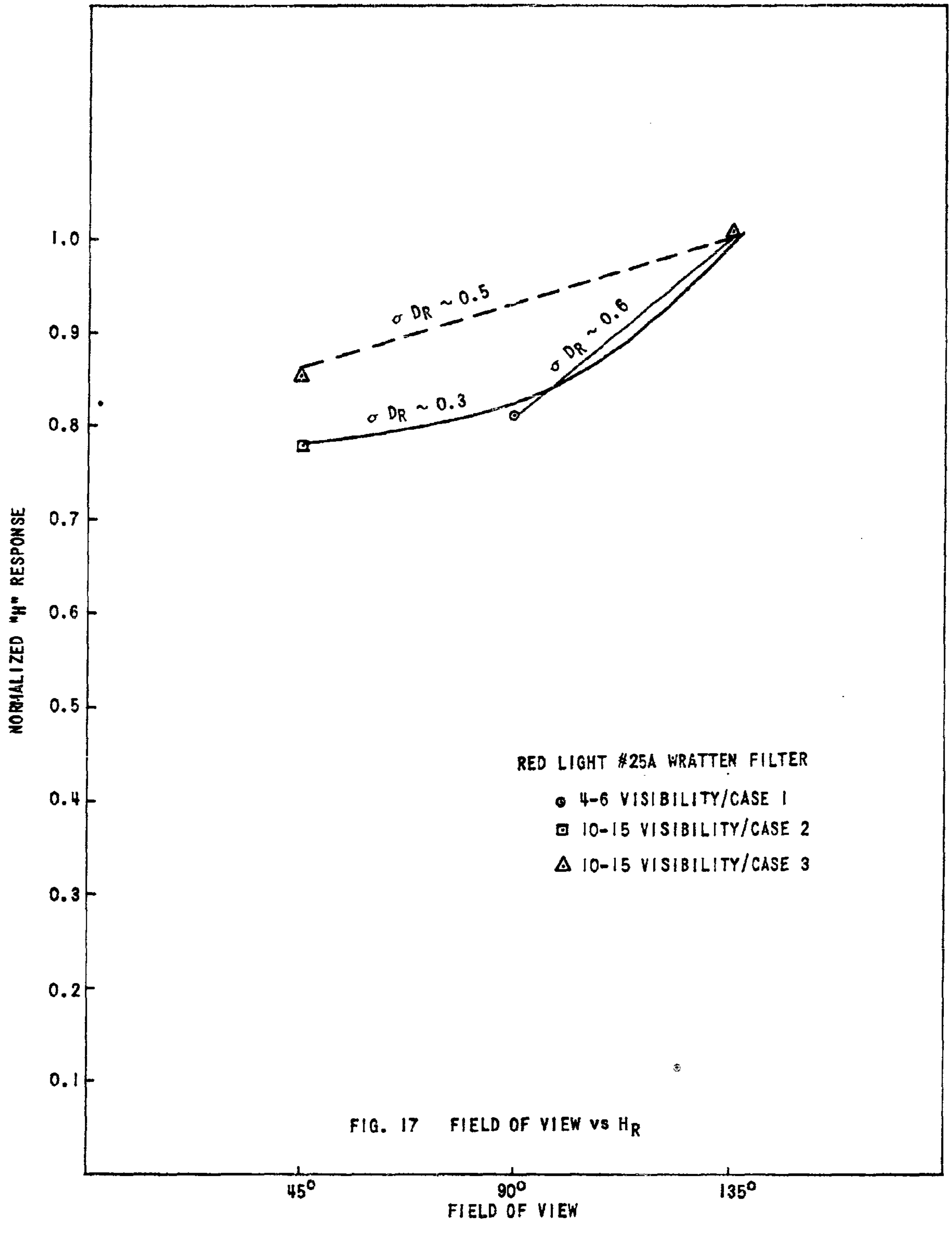

FIG. 17 FIELD OF VIEW vs H_R

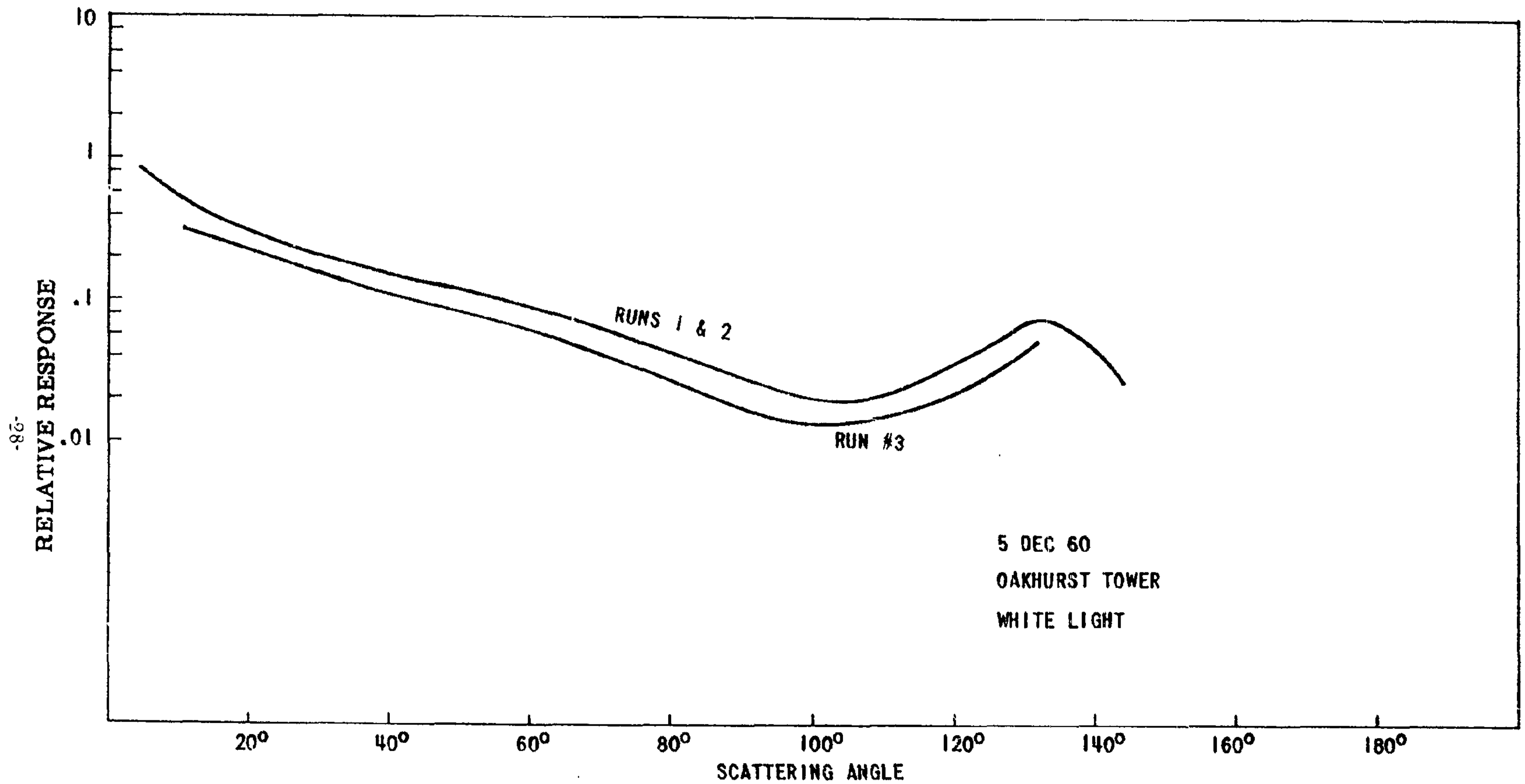

Figure 18 POLAR NEPHELOMETER MEASUREMENTS

The effects of multiple scattering have been considered, although only one empirical case of its probable occurrence appeared. Much further work is necessary in this aspect to arrive at any quantitative conclusions. Indications are, however, that values of H and H' further increase as the overall effects of multiple scattering predominate, while all other weather factors other than the optical path remain the same.

Further work is also necessary to establish a quantitative relationship between the field of view of the receiver versus the ratio of indirect to direct visible radiation under differing weather situations.

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Army Signal Research and Development Laboratory
Fort Monmouth, New Jersey
DIRECT AND INDIRECT VISIBLE RADIATION YIELD FROM A POINT SOURCE UNDER DIFFERENT WEATHER CONDITIONS by Israel Cantor, April 1962, 29p. incl. illus. table, 8 refs. (USASRDL Technical Report 2270) (DA Task 3A99-27-005-13)
Unclassified Report

Measurements of ratios of scattered to direct thermal radiation in the visible region were made on 17 nights during the period from October 1960 to February 1961, at Oakhurst, New Jersey, between two and three miles west of the ocean shoreline. Source-to-receiver distances of approximately one and two miles were involved, with general weather conditions varying from close to two miles visibility, snow-covered ground, and overcast skies, to clear skies, no snow, and visibility greater than 20 miles.
(over)

UNCLASSIFIED

1. Direct radiation
2. Scattered radiation
3. Multiple scattering

I. Cantor, Israel
II. Army Signal Research and Development Laboratory, Fort Monmouth, New Jersey
III. DA Task 3A99-27-005-13

UNCLASSIFIED

Results indicate situations where the indirect or scattered radiation is appreciably greater than the direct radiation. Tentative empirical relationships are derived for a 180° receiver field of view in a hazy atmosphere for some of the cases where no snow and cloudless skies exist, and compared with those of several previous investigators in the field. Results are also presented for cases involving snow-covered ground and/or clouds. An empirical relationship is tentatively developed for the situation involving only the presence of snow. In addition, some consideration is given to the multiple-scattering problem.

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